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Remote Measurements of Practical Length Standards Using Optical Fiber Networks and Low-Coherence Interferometers

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Practical length standards are remotely measured using a tandem low coherence interferometer through an optical fiber network for communication of about 20 km length between Tsukuba City and Tsuchiura City in Japan. The reference low-coherence interferometer is installed at the National Institute of Advanced Industrial Science and Technology (AIST) and the measurement interferometer with a gauge block of 100 mm nominal length is installed at a calibration laboratory in Tsuchiura City. The optical fibers work as a common path for the tandem interferometric system. Interference fringes are generated when the optical path difference between the reference and measurement interferometers is equal, and thus the gauge block is measured within a standard uncertainty of 46 nm remotely. [DOI: 10.1143/JJAP.47.8590]

KEYWORDS: remote calibration, fiber networks, low coherence interferometer, tandem interferometer, practical length standards

1. Introduction

In the metrology fields of science and industry, *in situ* and precision length measurements are strongly demanded for extending the reliability of experimental measurement data and improving the quality of production devices and systems. In the case of practical length standards, high-grade standards should be calibrated in standard metrology institutes using a conventional interferometer[1] with accuracy on the 10^{-7} order. At present, the length standard is supplied on the basis of the Japan Calibration Service System (JCSS) with a series of standards, ranging from "the national standards (iodine-stabilized He–Ne laser)" to a "practical stabilized laser" and artificial end standards such as a gauge block. In particular, gauge blocks are most widely used as practical length standards. Currently, gauge blocks under calibration are sent to standard metrology institutes or calibration laboratories. This is time-consuming and there is possible loss or damage of the gauge blocks; therefore, this system is inefficient.

Low-coherence interferometry has possibilities of space positioning and surface profiling with a high accuracy, and has been studied by many researchers.[2,3] Fortunately, combining the techniques developed in the long history of low-coherence interferometry with optical fiber networks and new broad-band light sources, a new system for high-accuracy length metrology may be expected.

We proposed a new technique using a tandem interferometer with a low-coherence light source for achieving remote measurement of length, in which two low-coherence interferometers are connected by a single-mode optical fiber in the wavelength range of 1500 nm.[4–7] In this study, the length of a gauge block is calibrated using optical fiber networks of 20 km length between the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba City and an accredited calibration laboratory (ACL) in Tsuchiura City. The optical path difference of one interferometer in the tandem low-coherence interferometer used is compared with that of the other interferometer through communication optical fiber networks. The length of the gauge block of 100 mm length at the ACL is remotely calibrated within a standard uncertainty of 46 nm with the reference standard interferometer at the AIST.

2. Measurement Principle

Remote measurements of practical length standards were carried out employing technology based on a tandem low-coherence interferometer using an optical fiber networks between the AIST in Tsukuba City and a calibration laboratory in Tsuchiura City, Ibaraki Prefecture, as shown in Fig. 1. We used a dark optical fiber of about 20 km length as a conventional communication fiber network. In this case, the optical fiber network serves as the complete common path for the probe and reference beams of one interferometer, and therefore the spectral chirping and polarization effects for these beams are the same. We can obtain the symmetrical interference fringe pattern, even if we use an optical fiber of large length such as one hundred kilometers. Moreover, we use no polarization effect of light. Assuming that the AIST is a standard laboratory with a reference interferometer, and the calibration laboratory in Tsuchiura City is an authorized supplier (or user), remote measurements were performed for a gauge block of 100 mm nominal length. Low-coherence interferometry is useful for space positioning by detecting the peak of the pattern of localized interference fringes because of the small coherence length of the light source used. The proposed technique is based on the principle of compensating for the optical path differences between the reference and measurement low-coherence interferometers. Interference fringes are generated when the differences between the optical paths of the two low-coherence interferometers are equal. If we use a broad spectral source, a sharp pattern of the envelope of interference fringes is generated, and then the central fringe is determined uniquely.

One drawback of the tandem interferometer is its low signal-to-noise ratio because the interfering part of the light used is 1/8 at maximum. In this experiment, low-coherence interference fringes are generated when the reference interferometer is scanned by 40 μm using a piezoelectric transducer (PZT). The amplitude of the central interference fringe sometimes fluctuates owing to air turbulence and

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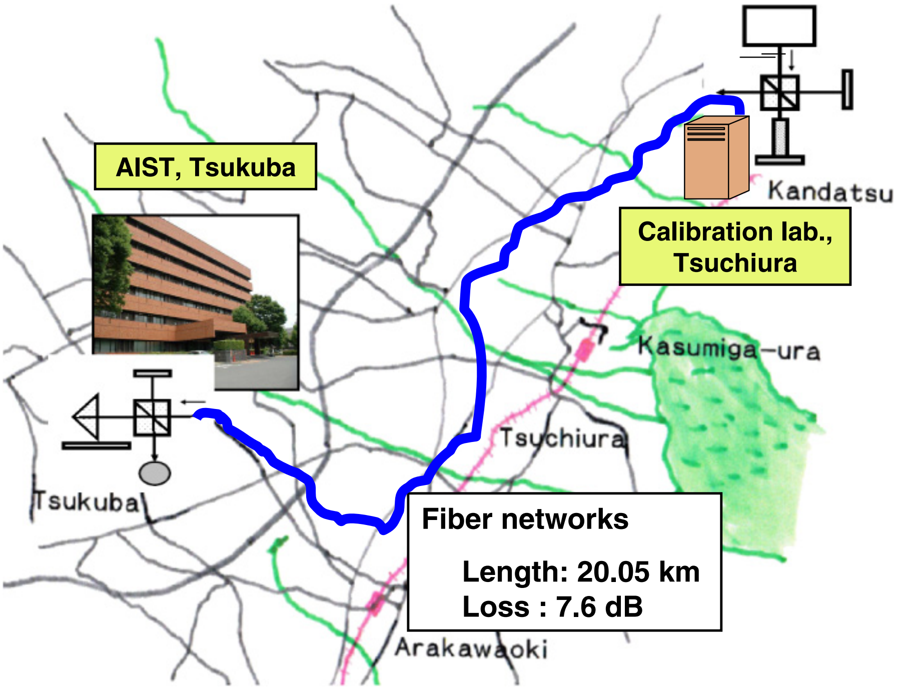

Fig. 1. (Color online) Outline of remote calibration system using optical fiber networks.

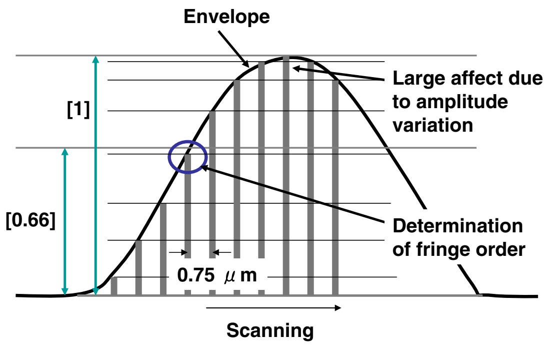

Fig. 2. (Color online) Proposed technique for determining the central fringe order of low-coherence interference fringes obtained.

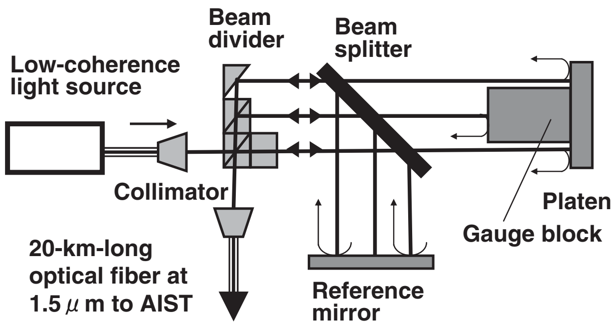

Fig. 3. Setup of the measurement interferometer.

mechanical vibration, and the center fringe does not correspond to the maximum amplitude of the fringes owing to small differences between fringes at the center, so the central interference fringe is not uniquely determined although the phase of the central interference fringe remains unchanged. Therefore, the order of interference fringe is determined at the steep envelop of the interference fringe pattern, because the amplitude difference of interference fringes is very large and its position is not strongly affected by the amplitude variation of the interference fringe generated, as shown in Fig. 2.

3. Experimental Procedure

The experimental setups of the new tandem interferometer are shown in Figs. 3 and 4. They consist of two Michelson-type interferometers, which are set in well air- conditioned rooms. One interferometer (measurement interferometer) has a gauge block of 100 mm nominal length, and the other interferometer (reference interferometer) has a traveling mechanism for generating low-coherence interference fringes. The interferometers are connected by a communication (dark) optical fiber in the wavelength range of 1500 nm, and the optical path difference of the tandem interferometer is compensated by the overall optical path differences between the two low-coherence interferometers. Low-coherence interference fringes are generated when the optical path difference of the tandem interferometer becomes zero. A light beam is introduced through a single-mode optical fiber and an optical-fiber circulator from an amplified spontaneous emission source (ASE) and is collimated to a diameter of about 7 mm diameter. The collimated beam is incident to the beam splitter (half-reflecting mirror) of the measurement interferometer after passing through complicated beam dividers (Fig. 3). Light beams through the beam splitter are incident on the gauge block and a paten plate, which are connected by wringing. Another beam hits the reference mirror of the measurement interferometer. The output beams from the measurement interferometer travel to the reference interferometer through the circulator and an optical fiber networks of about 20 km length in the fields, as shown in Fig. 4. We utilized the optical fiber for general optical communications by rental from Tokyo Electric Power Company.

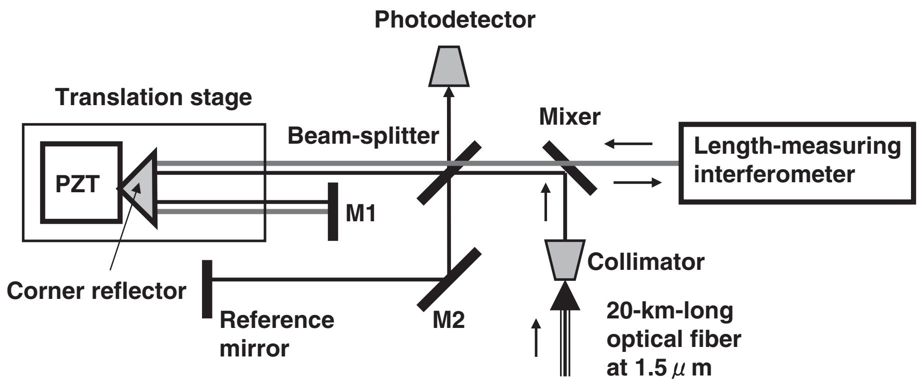

Fig. 4. Setup of the reference interferometer.

After passing through the optical fiber networks, the optical beam is collimated to a diameter of about 7 mm. The corner reflector of the reference interferometer is mounted on a piezoelectric transducer to scan an optical path of over 40 μm length, and is then mounted on a linear traveling stage to change the optical path difference for measuring the optical differences, L_g and L_p, between the surface positions of the gauge block, platen and reference mirror. The output beam of the measurement interferometer is detected by an InGaAs photodiode (sensitive area; 0.3 mm in diameter) after passing through a single-mode optical fiber and then the detected signal is input to a computer after electric amplification and filtering. Finally, the length of the gauge block is determined by ($L_g - L_p$).

The light source used was generated by the ASE (Thorlabs SOA240), whose center wavelength and full width at half maximum were 1500 and 100 nm, respectively. The output power was about 7 dBm. The light is linearly polarized, but the effect is not utilized in this tandem interferometer. The experiments were performed on different days using different setups of optical fibers. The output power from the interferometer was about −13 dBm, which was reduced to about −21.5 dBm by the 20-km-long optical fiber.

The optical path difference in the reference interferometer was changed by moving the corner reflector using a linear stage (Sigmatec FS3150) and a PZT (PI Polytec P-621.1CL). The peak position of the pattern of low-coherence interference fringes may accurately be determined. From this result and the technique shown in Fig. 2, the fringe order was uniquely determined at a success rate of 97% in this experiment. As a result, we can determine the length of the gauge block with a high accuracy. Then the phases of the center interference fringes were obtained with standard deviations of 5–15 nm length. Therefore, this method uses the phase refractive index of air to correct the optical measured length to the geometrical length. Measurements are achieved when the optical path difference of the reference interferometer is equal to the difference between the optical paths of the reference and measurement arms on the surface of the gauge block, and then the difference between the optical paths of the reference and measurement arms on the surface of the platen in the measurement interferometer. The displacement of the corner reflector of the reference interferometer was measured using an HP length-measuring interferometer (Agilent 5517B) at a resolution of 1 nm and an uncertainty 0.1 ppm of the wavelength.[8)]

In the measurement interferometer, air temperature was measured with an uncertainty of 18 mK (3 times the catalog value) using a temperature sensor (Hart Scientific 1529 chub-E4). Also, air pressure was measured with an uncertainty of 40 Pa (2 times the catalog data) using a pressure sensor (Yokogawa Electric MT-110). The humidity of the experimental room was controlled within 10%. Therefore, the refractive index of the air under evaluation was calculated with a standard uncertainty of 0.13 ppm by the modified Edlén's equation.[9,10)] Moreover, considering that the thermal expansion coefficient of the steel gauge block, the alignment error of the optical beam and the wave-front distortion of the interferometer are 10.8×10^{-6}/K, 0.6 mrad, and 13 nm, respectively, a combined standard uncertainty of the measurement interferometer is 32 nm for a gauge block of 100 mm nominal length. In this case, the optical beams were aligned by detecting the beam position over 5 m propagation in air.

On the other hand, the errors of the air sensors are negligible in the reference interferometer, because the difference between the refractive indices of air in the wavelength region of the visible and near-infrared spectra is only about 1.3 ppm. Therefore, the uncertainty due to the air refractive index is very small to be a secondary effect. Considering the wavelength error of 0.1 ppm,[8)] the dead path length of 50 cm, the beam alignment error of 0.4 mrad, the wavefront distortion of 13 nm, and the measurement error of interference fringe of 26 nm due to $111\,\text{nm}/\sqrt{18}$ in uncertainty estimation, we can estimate a combined standard uncertainty of 32 nm for a 100 mm length. Finally, an overall combined standard uncertainty of the system becomes 46 nm for a length measurement of the 100-mm-length gauge block. The list of the error budget estimated is shown in Table I.

4. Results and Discussion

An example of interference fringes obtained by this system is shown in Fig. 5. The signal-to-noise ratios of the interference fringes are high to be about 50. The experimental results for almost one month are shown in Table II and Fig. 6. The deviations of the obtained data from the nominal length were given, with the value of −116 nm obtained by the traditional method of the AIST. The standard

Table I. Error budget list of uncertainty for 100-mm-long gauge block.

Measurement interferometer		ppm	nm	nm
Air temperature measurement	18 mK	0.02	2	
Air temperature distribution	50 mK	0.05	5	
Air humidity measurement	10%	0.01	1	
Air pressure measurement	40 Pa	0.11	11	
Uncertainty of refractive index equation		0.05	5	13.3
Thermal expansion correction	18 mK	0.19	19	
Alignment error	30 μm/50 cm	0.18	18	
Wavefront distortion	13 nm		13	29.2
Standard uncertainty				32.1
Reference interferometer		ppm	nm	nm
Wavelength uncertainty		0.1	10	
Dead path effect of interferometer	50 cm	0.05	5	
Alignment error	2 mm/5 m	0.08	8	
Wavefront distortion	13 nm		13	
Measurement of fringes	26 nm		26	
Standard uncertainty				32.2
Combined standard uncertainty	—	—	—	45.5

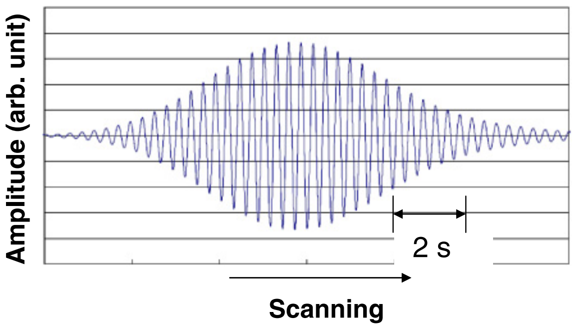

Fig. 5. (Color online) Typical example of low-coherence interference fringes obtained.

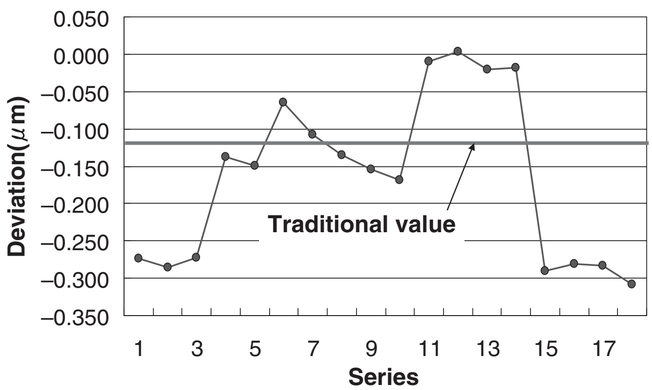

Fig. 6. Experimental data of deviations from nominal length and length obtained by the traditional method (see Table I).

Table II. Measurement results obtained for one month.

Series	Day	Time	Number of measurements	Average (μm)
1	Sep.4	13:29	5	−0.273
2	Sep.5a	9:07	5	−0.285
3	Sep.5b	13:39	5	−0.272
4	Sep.5c	22:19	15	−0.138
5	Sep.6a	23:14	5	−0.149
6	Sep.6b	22:00	15	−0.065
7	Sep.7a	10:19	10	−0.108
8	Sep.7b	17:31	5	−0.135
9	Sep.8a	9:49	5	−0.154
10	Sep.8b	13:31	10	−0.168
11	Sep.21	22:01	10	−0.010
12	Sep.22a	9:48	10	0.004
13	Sep.22b	20:03	15	−0.021
14	Sep.25a	10:06	5	−0.018
15	Sep.25b	18:01	15	−0.290
16	Sep.28	13:44	10	−0.281
17	Sep.29	9:51	10	−0.283
18	Oct.02	11:56	10	−0.308
			Average	−0.164
			Standard deviation	0.111

deviations of data for several hours are very small to be 5–15 nm, but the standard deviations of the data for terms longer than half a day are slightly large to be 111 nm and really are larger than the value estimated by the uncertainty budge list. However, the average value of the experimental data was very small to be within 0.1 ppm compared with that obtained using the traditional calibration system of the AIST, whose combined uncertainty ($k = 2$, a level of confidence of approximately 95%) is 13 nm for a 100-mm-long gauge block without a ringing effect. Therefore, the effect of the outside optical fiber is very small in this system.

Remote measurements of a gauge block were achieved using optical fiber networks for general communication. The total loss of the fiber networks for a 20-km-long optical fiber is not large at 7.6 dB. However, the losses of the reference and measurement interferometers are large at roughly 20 dB. In order to use longer optical fibers, it is important to reduce the losses of the interferometers. In this case, we can also utilize optical amplifiers between the reference and measurement interferometers to increase the power of light.[7)]

The standard deviations of the data obtained within about 3 h are sufficiently small at 5 to 15 nm. Therefore, the effects due to mechanical vibrations of the fiber are small. However, in the case of the data obtained after half a day, the averages were sometimes changed by several tens of nanometers though the standard deviation of each data set was kept small. Since the expanded uncertainties (coverage factor $k = 2$, a level of confidence of approximately 95%) of this remote measurement method proposed and the traditional method were 91 and 13 nm, respectively, the combined standard uncertainty was 47.5 nm. In Table I, since the difference between this method (-164 nm) and the traditional method (-116 nm) is 48 nm, the ratio of 48 to 95 nm is 0.51.[11] The experiment is reasonable due to the ratio of $0.51 < 1$, though the dispersions of the measurements are slightly large. The change does not directly depend on the variation in air temperature in the field. We can consider the effects as follows: 1) the stability of fiber connectors without fusion splicing, 2) the transformation of the interferometers, and 3) the change in the posture of the gauge block. To resolve these sources, much experience and data obtained under different conditions are required. Moreover, since the rental term of optical fiber network is limited, we utilized sensors for obtaining the conditions of measurement. Therefore, we estimated the uncertainties of the sensors used using our experience and the catalog values. To improve the reliability of this remote measurement method, the calibration of the sensors is required on the basis of the national standards.

Moreover, an automatic measuring system and a simple calibration procedure are required to accept the ISO/IEC 17025 and a low-cost calibration is also important, though the rental fees of dark fibers are very expensive. At present, we are planning to conduct experiments with low cost fibers, similar to that used in the general Internet. Anyway, the remote calibration of the gauge blocks used was achieved with a standard uncertainty of 46 nm in the gauge block of 100 mm nominal length. Therefore, this method can be applicable to the remote and *in situ* measurement in factories and other things.

Although the best highest measurement uncertainty is as small as 30 nm (100 mm, expanded uncertainty, $k = 2$) in the conventional "take-in" calibration, the accuracy of the present measurement is fairly adequate for practical use, demonstrating the effectiveness of the remote-calibration technique for length standards via the optical fiber network. The success of the remote calibration technique will allow users to acquire a traceable length for the national standards through the optical fiber network while keeping their own length standards in the laboratory. Moreover, this makes it possible to avoid the risk of damage or loss in the course of transportation, as well as to reduce the number of days required for calibration. The utilization of the optical fiber network will make many users including small and medium enterprises and research laboratory accessible to the national standards for length.

5. Conclusions

We have realized the transmission of information on practical length standards through an optical fiber network for communications of 20 km length between Tsukuba City and Tsuchiura City in Ibaraki Prefecture, Japan. A tandem interferometer developed was composed of two traditional low-coherence interferometers, which were connected by a single-mode optical fiber network. The length of the gauge block of 100 mm was first measured remotely with a standard uncertainty of 46 nm. The uncertainty of measurements can be improved by accurate measurements of environmental conditions and good performance design in each low-coherence interferometer.

The success in the remote calibration technology will allow users to acquire a traceable length for a national standard through the conventional optical fiber network, while keeping their own length standards in the laboratory.

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